Adaptive Fuzzy Spray and Wait: Efficient Routing for Opportunistic Networks

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Abstract— **The technological advancement in the area of wireless networking is ultimately envisioned to reach complete and seamless ubiquity, where virtually every point on earth will need to be covered by Internet access. Low connectivity environments have emerged as a major challenge, and accordingly Opportunistic Networks arose as a promising solution. While these networks do not assume the existence of a path from the source to the destination, they opportunistically utilize any available resource to maximize throughput. Routing protocols in such environments have always tried to target an increased delivery probability, a shorter delay, and a reduced overhead. In this work, we try to balance these apparently conflicting goals by introducing "Adaptive Fuzzy Spray and Wait", an optimized routing scheme for opportunistic networks. On top of the overhead reduction, we argue that the spray-based opportunistic routing techniques can attain higher delivery probability through integrating the adequate buffer prioritization and dropping policies. Towards that purpose, we employ a fuzzy decision making scheme. We also tackle the limitations of the previous approaches by allowing a full-adaptation to the varying network parameters. Extensive simulations using the ONE (Opportunistic Network Environment) simulator** [1] **show the robustness and effectiveness of the algorithm under challenged network conditions.**

Keywords: Opportunistic Networking; Routing ; Delay Tolerant Networks; Fuzzy Logic

I. Introduction

As wireless and mobile technologies are becoming increasingly pervasive, an uninterrupted connectivity in mobile devices is becoming a necessity rather than a luxury. Towards that goal, the field of Mobile Ad hoc NETworks (MANETs) has emerged as a possible solution that aims at improving communication in many application environments, such as intelligent highways, home automation, and wildlife tracking. Nevertheless, the traditional communication paradigms in MANETs have always considered nodes' mobility as an issue to deal with rather than an opportunity to exploit. In addition, the assumption of an existing path between the source and the destination nodes has proven to be invalid when it comes to challenged networks. Such networks are characterized by intermittent connectivity, large delays, low data rate, the absence of end-to-end path, and a high cost of infrastructure deployment [2]. Accordingly, the field of opportunistic networks evolved as a promising solution that is devised to opportunistically utilize any possible resource available to achieve faster data delivery and to maximize throughput.

At the heart of such networks is the problem of multi-hop message routing from source to the destination. This is also one of the topics that received a lot of attention from the research community. The ultimate goal of opportunistic routing has been to achieve a simple, easily deployable scheme with low overhead, high delivery rate, and short delay. Some approaches work on duplicating the message in the network, thus increasing the delivery probability at the expense of huge communication overhead. Other approaches employ highly intelligent forwarding techniques, at the expense of extra complexity and processing delay. There exist algorithms, called *spray-based*, which try to minimize the overhead of the former approach by reducing the message duplicates to a limited but sufficient number at the price of lower delivery probability.

The existing spray-based approaches have mainly concentrated on optimizing the number of message copies to be disseminated in the network, in order to balance the two goals of minimizing congestion and maximizing delivery rates. While this methodology has kept them simple and effective, it did not take into account other techniques that increase the message delivery probability in parallel with overhead reduction. Specifically in the challenged networks with high level of contention, short contact time, and low bandwidth, the number of messages that can be shared when two nodes meet is limited. The need arises for a prioritization mechanism that promotes messages in a way to increase their probability of reaching their destination. This work at the prioritization level should be also accompanied with a dropping policy that ensures fairness among the messages in the buffer. Furthermore, to enhance the spraying mechanism, the nodes should have good estimates of the general network parameters, such as the number of nodes, as these should be taken into account in the dynamic choice of the number of copies to spray.

We propose *Adaptive Fuzzy Spray and Wait (AFSnW)* a novel routing mechanism that smartly integrates the overhead-suppression and buffer management policies into an adaptive protocol that includes a local network parameters estimation mechanism. It is novel in the sense that it breaks the loop that spray-based approaches are turning in, and pauses the search for optimized replication to investigate other opportunities of improved data delivery, namely buffer management and parameters adaptability. Our contributions are shown to be effective through an extensive set of simulations using the ONE simulator [1].

In the next section we review the literature for related work in the field of opportunistic routing. In section III, we present the details of the proposed Adaptive Fuzzy Spray and Wait (AFSnW) algorithm. Section IV describes the simulation environment and evaluates the results. Finally, we give a comprehensive conclusion and ideas for future work in section V.

II. RELATED WORK

Challenged networks have two basic characteristics: the absence of a direct path from source to destination and the intrinsic mobility of the nodes. Opportunistic routing schemes try to tackle the first point through dynamic, hop-by-hop route construction. Each mobile node chooses to forward the message to a subset of its neighbors. The mobility feature is exploited as an opportunity to carry messages over the sparse or disconnected network, thus increasing the probability of message delivery.

Based on the taxonomy of Figure 1, we classify the routing protocols into two categories: those used in completely flat ad hoc networks (*without infrastructure*) and those which make use of certain types of infrastructure for data delivery (*with infrastructure*). Infrastructure-based routing relies on the presence of specialized static or mobile agents for enhancing network connectivity. Accordingly, they are well-suited for networks restricted to a certain geographical area such as wildlife tracking networks [3]. Nevertheless, their dependence on a dedicated infrastructure limits their utility in sparse mobile networks, such as pedestrian internet usage under highly intermittent connectivity. Infostation [4] is an example of a system employing fixed infrastructure. Even in mobile infrastructure-based routing, such as the Data-MULE system proposed in [5], the mobile agents, called MULEs gather data from sensors and carry them to a static host. Therefore, their hierarchy usually terminates at a fixed infrastructure. Routing schemes that operate without an infrastructure have the scalability feature in the sense that the network can extend to wherever the mobile nodes can move. They are also cost efficient, as they don't necessitate the existence of an infrastructure.

In our taxonomy, we further differentiate between *forwarding* strategies and *dissemination* strategies. Forwarding routing strategies attempt at delivering the only copy of each message along the best path to the destination. They exploit context information about the message neighborhood in order to choose the next hop. For example, Motion Vector (MoVe) protocol [6] uses location and velocity information. Due to the inherent nodes' mobility and the network contention, this copy is very likely to be dropped or to have a high latency before reaching the destination. Therefore, these techniques generally suffer a low delivery probability. Dissemination-based techniques are defined in [7] as an attempt to deliver a message through diffusing it over the whole network. The intuition behind such a strategy is that the presence of more replicas increases the delivery probability. However, this usually comes at the cost of increased congestion and higher storage requirements. The class of *automatic dissemination* routing strategies forwards replicas to the carrier's neighbors, regardless of the latter's prospective delivery probability to the destination. On the other hand, *selective dissemination*, goes a step further by restricting the message forwarding to the set of neighbors with higher delivery chances than the current

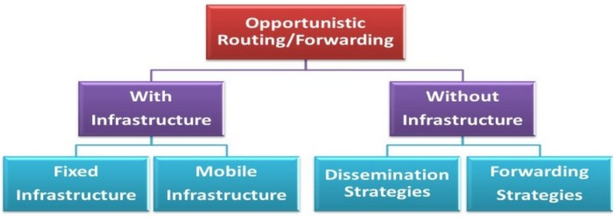

Figure 1: Routing techniques taxonomy

custodian. These chances are usually calculated based on history of encounters and/or contact probability as in PROPHET [8], Meeting and Visits (MV) [9], and MaxProp[10] routing protocols. Another subclass of selective dissemination is social-based schemes, which exploit the user's relation to different social groups [11]. The main limitations of selective dissemination schemes are their complexity of implementation, processing overhead, and need of knowledge of global parameters.

The extreme case of automatic dissemination is Epidemic Routing (ER), which was first introduced in the opportunistic routing field by Vahdat and Becker in [3]. In this technique, messages are spread in the network in a way similar to viruses, where nodes get infected when contacting other infected nodes. A node recovers from the infection when it transmits it to the destination node, thus becoming immune to further infections. Fuzzy Spray (FS) , proposed in [12] uses fuzzy decision making to prioritize messages in the nodes buffer in an attempt to increase the delivery probability. For that purpose it uses two locally available parameters, namely Forward Transmission Count (FTC) (defined later in this paper) and message size to assign priorities to the messages in the buffer. The protocol name might be misleading, as it is more of unlimited, but prioritized, dissemination than a spray-based approach. It resembles epidemic routing in its large overhead, as there is no limit on the number of copies that can be replicated per message. Another protocol that performs buffer prioritization is MaxProp, which takes into consideration two factors: promoting less disseminated messages and increasing delivery likelihood [10].

On the other hand, spray-based approaches attempt at reducing the routing overhead by limiting the number of message replicas, without depending on any extra knowledge or complex processing. Spray-and-Wait (SW) [13] is an example protocol, which consists of two phases, as indicated by its name. In the spray phase, the node floods the network with (L-1) replicas of the message, where L is a protocol specific parameter. In its optimal (binary) version, dissemination occurs by relaying the task of sending half of the remaining copies to the recipient node. If the destination is encountered, the algorithm terminates. When one message remains, the wait phase begins in which the message is only forwarded when the node comes in contact with the intended destination. One important problem in this protocol is how to optimally select L based on the network parameters available to the node. The authors of [14] show through analytical modeling of Spray and Wait that closed form solution of optimal L can be found assuming a target delay, through solving the following third degree equation in L:

$$\left(H^3{}_M\text{-}1.2\right)L^3+\left(H^2{}_M\text{-}\frac{\pi^2}{6}\right)L^3+\left(a+\frac{2M\text{-}1}{M(M\text{-}1)}\right)L=\frac{M}{M\text{-}1} \qquad (1)$$

where M is the number of nodes, H_n is the nth Harmonic Number (i.e. $H_n = \sum_{i=1}^{n} \frac{1}{i}$), and a is the ratio of the expected delay of SW to the optimal delay that can be achieved.

The work in [15] refines this modeling to incorporate wireless contention. The basic parameter on which L depends is M, the number of nodes in the network. In topologies with high mobility, M is a variable parameter, as nodes frequently enter and leave the network. Therefore, an important factor in this selection is for each node to have a good approximation of the number of nodes present in the general network.

III. Adaptive Fuzzy Spray and Wait Algorithm

From the above survey of opportunistic routing schemes, we notice that the spray-based approaches combine several advantages. First, they are built over flat adhoc networks that do not require a dedicated infrastructure, hence their scalability. Second, they are dissemination-based, so they attempt at increasing the delivery probability by replicating the message in the network. Third, they employ automatic dissemination, where the complexity and processing overhead are very low. Forth, they limit the overhead by restricting the number of copies in the network. Nevertheless, they suffer from several limitations. First, to the best of our knowledge, there have not been any attempts to provide new means for improving their efficiency, other than adjusting the number of replicas. The work is mainly on limiting the overhead, assuming that the improvement in probability of delivery will follow. Second, these schemes necessitate a good local approximation of the network parameters for the purpose of optimizing the choice of L. Third, these protocols have not been designed for adaptability to the changing network conditions.

Adaptive Fuzzy Spray and Wait (AFSnW) is a spray-based routing mechanism that incorporates the above advantages and tackles the limitations of the spray-based approaches. Contrary to the traditional set theory, Fuzzy Set Theory allows partial membership to sets (i.e. belonging to a set to a certain degree). We have employed a fuzzy-based message prioritization in the buffers, inspired by the one utilized in [12]. As we show later, this mechanism would not have been as effective and fair if we did not add to it the appropriate dropping policy. By this, we broke the loop that spray-based approaches have been turning in (i.e. of focusing mainly on optimally selecting L) and showed that it is better to seek new ways of improving efficiency. We have also incorporated a new local estimation for the network conditions, which made it easier to adapt the different parameters to the general network.

We summarize our algorithm in the following:

1) When a mobile node receives a message, the value of L is extracted and divided by two, and the message is updated with the new value (L_{new}=L/2). If the node is the message originator, then the current approximation of L based on equation (1) is used.

2) As long as the destination is not encountered, the mobile node forwards up to ($L_{new} - 1$) replicas of the message. When only one copy is present, it is only forwarded to the destination.

3) The messages are always sorted in the buffer according to the priority level determined by the output of a fuzzy decision making function. Upon contact with other nodes, messages are exchanged according to this order, and the local parameters are updated.

4) When the buffer is full, the messages are dropped according to a random order with respect to priority level (such as dropping the oldest message).

We now move to discussing the details of the major steps of the previous algorithm:

A. *Buffered Messages' Prioritzation*

Challenged networks are characterized by short contact time between the nodes, resulting from high speeds or high contention. Our algorithm uses fuzzy logic as a technique to prioritize messages in the buffer. This technique has been shown to be efficient in [12]. The rationale behind this prioritization is twofold:

1) Messages which propagated enough in the network should have less priority in order to give a chance for less disseminated messages.

2) Large messages should have less priority in order to maximize the number of messages that can be successfully transmitted in each short contact opportunity. It is argued in [12] that this approach reduces partial transmissions and increases the number of packets delivered.

This rationale is reflected in two parameters: *Forward Transmission Count* (FTC) and *Message Size*, which are both local to the nodes:

1) **FTC** is an indicator of the number of duplicate copies of a message in the network. Its initial value is 1 and is incremented on both the sender and the receiver sides upon successful transmission. A message with a high FTC should be given lower priority since the Expected Additional Coverage (EAC) is lower than that of messages with lower FTC.

2) **Message size** is an easily calculable parameter on each node. It usually depends on the application type.

Fuzzy decision making is typically used in such cases, where heterogeneous parameters have to be integrated to reach a certain classification. It also allows to easily extend the

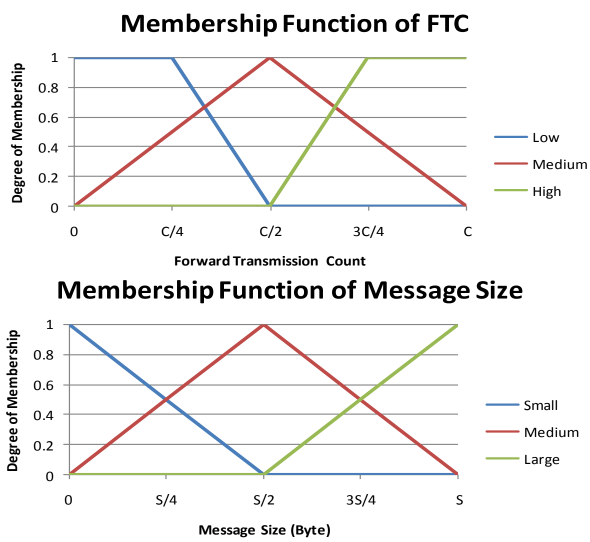

Figure 2: Membership functions for the fuzzy scheme

Table I: Fuzzy rule base

Priority Level		FTC		
		Low	Medium	High
Message Size	Small	P0	P3	P6
	Medium	P1	P4	P7
	Large	P2	P5	P8

prioritization process to include more inputs. The interested reader can refer to [23] for a comprehensive survey of fuzzy logic and its applications. The fuzzy membership functions we used are similar to the ones employed in [12] and are presented in Figure 2, where the message size has three levels: small, medium, and large. Similarly, FTC has three levels: low, medium, and high. Fuzzification is done according to the triplet: (left-shoulder, triangle, right-shoulder). Such technique is usually preferred for its ease of implementation in microprocessors [16]; thus it is well crafted for the constrained mobile devices at hand. Table I shows the rule base used in the fuzzy decision making (P0 is the highest priority level while P8 is the lowest one).

B. Dropping Policy

An important buffer management decision is the dropping policy to be employed. We have chosen to use a dropping policy which is randomized with respect to priority, instead of the intuitive drop-least-priority scheme. The rationale behind this policy is that it renders our algorithm fairer. In the drop-least-priority policy, messages of low priority will most probably have their replicas present in other nodes with similar priority levels. Accordingly, they will be always dropped upon the arrival of new messages to a full buffer. One might question the utility of prioritization with such a dropping mechanism. However, the role of prioritization in our scheme is mainly to dictate the order in which messages are exchanged during the short contact time. Through simulations, we show the efficiency of this prioritization-dropping policy combination, which proved to be effective in ensuring fairness while preserving the gain of high delivery probability.

C. Adaptable Network Parameters

Making good approximations of the message size and the number of nodes is critical for the efficiency of the fuzzy scheme and for the optimization of the value of L. Fuzzy Spray [12] assumed that the message size maximum boundary is S=100000 bytes while the FTC maximum boundary C is 10% of the number of nodes. The weakness of this algorithm appears in the case when the majority of messages have sizes much smaller or much larger than the pre-defined fixed value S, as they will all be mapped to *Small* or *Large* respectively, and the message size becomes irrelevant to the priority. Consequently, we employ the powerful technique of adaptive fuzzy logic [17] to adapt the boundaries of the fuzzy membership functions to a locally calculated average message size, calculated similar to the RTT estimation in TCP.

We have also devised a scheme for each node to estimate the total number of nodes by the number of unique IDs of message originators which have been forwarded through it. Using this estimate of the number of nodes allowed us to adapt the boundary of the FTC membership function. This estimate better served to adjust L to its optimal value.

IV. EVALUATION

In what follows we present our evaluation methodology, discussing the adequate choice of network parameters to reflect the challenged environments under investigation. Then we present and analyze the results that prove the efficiency of our novel scheme in increasing the probability of delivery and improving the delay while keeping the overhead at low levels.

A. Simulation Setup

Simulations were performed using the *Opportunistic Network Environment* (ONE) simulator [16], which is specifically designed for challenged networks' evaluation. The choice for ONE over ns-2 or OPNET was motivated by its widespread use in the opportunistic networking community due to its generic support for DTN testing.

Contrary to the simulations in [12], which assumed practically unlimited buffer space (250 MB with 10-100KB messages), we use limited buffers to accurately model the constrained environment and test the effectiveness of the prioritization scheme. Our setup assumes that, on average, the buffer can accommodate around 50 messages, which is comparable to the simulation environments in previous works where contention is studied [9, 10, 20-22]. Moreover, since it has been established in [12] that FS outperforms all of MaxProp, PROPHET and Epidemic Routing, for the mobility model under study, we restricted our comparison to FS and SW. Additionally, in order to reproduce the results of [12], we used the Random Waypoint mobility model.

For fair evaluation, and unless otherwise specified, we compare against our implementation of a protocol we call AFS (Adaptive FS), an adaptive version of Fuzzy Spray modified via the same techniques of Section III-B. In order to assess the protocol under variable conditions, the default parameters presented in Table II were varied each at a time in our simulations, as we show below.

B. Simulation Results

1) *Effectiveness of Priority Scheme*

First, we start by verifying that prioritizing messages which have not been delivered enough is actually efficient. For that reason, we compare AFSnW, with our priority scheme described previously, to a one with the reverse priority scheme policy. By reverse policy, we mean prioritizing messages that have the highest dissemination levels. This policy is also

Table II: Simulation environment parameters

Hardware Components	• Intel Xeon Quad core 2.66 GHz • Operating System: Microsoft Windows Vista
Environment	• Number of nodes: 60 • Buffer size: 1Mb • Message sizes: 10→100Kb • Message creation interval : 25→ 35s • Simulation duration: 12 hrs.
Mobility Model	Random-Waypoint • waiting time: 0 → 120s • speed: 2.7 → 13.9 m/s
WLAN Model	• Transmission range: 30m • Transmission rate: 1Mbps
Spray-based Routing Scheme Parameters	• Total copies disseminated per message : L=24 (unless stated otherwise)

justifiable by the following argument: these messages are in a good position in terms of their degree of dissemination and need a small push to reach the destination. Consequently, they should be given primary concern since, in constrained conditions, if messages remain for long durations in the buffers, they may be dropped. Hence, the overhead paid for their dissemination might be lost. In our scenario, simulations showed that the priority scheme, based on promoting less disseminated messages is more efficient. This result is illustrated in Figure 3, where we can notice that AFSnW outperformed the opposite priority scheme (denoted by AFSnW.O) and resulted in larger delivery probability at the optimal value of L for each curve. This figure illustrates also the point that having more replicas does not always lead to a better delivery probability, due to the increased congestion at high values of L.

2) *Effectiveness of Buffer Prioritization*

We proceed by verifying our claims regarding the effectiveness of AFSnW. The graphs of Figure 4 were performed as a function of time, showing the progress of the metrics during the simulation. Not only did AFS show a very high routing overhead, it has also performed worse in terms of delivery probability. SW and AFSnW result in similar routing overhead due to the same limiting parameter L. However, AFSnW outperforms all in terms of delivery probability. Note that these results appear at odds with those presented in [12], due to the more accurate challenged model we use, as discussed previously.

To compare the routing schemes in terms of latency, we divert from the general trend (used in [8-10,12,13]) of using average delay as a metric. The problem in this approach arises from the fact that different routing schemes result in different delivery probabilities. From a delay perspective, the system with higher delivery rate has succeeded in changing the delay of some of its previously undelivered packets from an infinite to a finite value. Accordingly, these packets might take more time to get delivered, but this time cannot be seen as a performance loss. This implies that a higher average latency does not necessarily mean that individual messages are getting delayed but that additional messages are being delivered. Consequently, fair average latency comparisons necessitate equal delivery ratio. Nevertheless, it is not practical to modify the simulation environement to result in same delivery probability for the different routing schemes. Accordingly, we decided to plot average latency per cumulative delivery probability as we have done in Figure 5. In this figure, averages are calculated with respect to the part of delivered messages that result in the corresponding cumulative probability. Thid figure shows that the delivery of messages is delayed in AFS more than in SW and AFSnW. The last two display similar latency for the same values of cumulative delivery probability. When this probability increases beyond the overlapping region, the delay in AFSnW remains lower than the supposedly infinite delay for the undelivered messages. Figure 4 and Figure 5 both verify our argument that AFSnW reaches higher delivery ratios than the other two, due to its buffer prioritization, parameters adaptation and controlled dissemination.

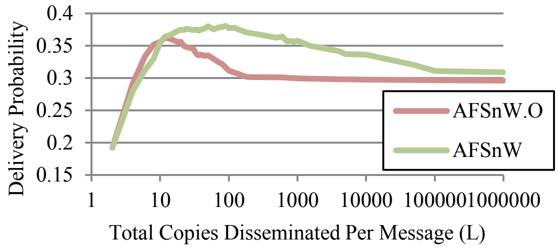

Figure 3: Comparison of opposite priority schemes

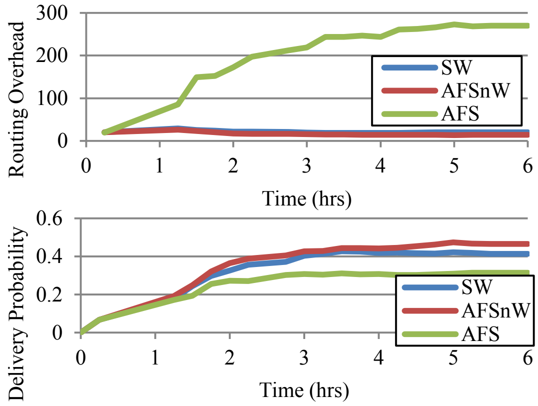

Figure 4: Routing overhead and delivery probability as function of time (L=12)

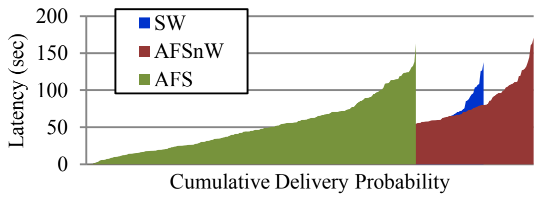

Figure 5: Latency vs. cumulative delivery probability

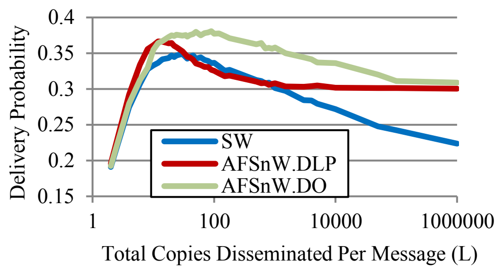

Figure 6: Effect of dropping policy on the

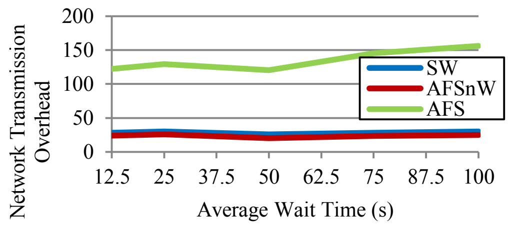

Figure 7: Overhead comparison by varying against average wait time of random waypoint

3) *Choice of Dropping Policy*

We now move to test our argument regarding the dropping policy that should accompany the prioritization scheme. For that purpose, we plot in Figure 6 the delivery probability with variable number of copies (L) for each of SW, AFSnW.DLP (with a drop-least-priority policy), and AFSnW.DO (with a drop-oldest policy). Practically, the latter policy is assumed to drop a message of random priority level. It is clear from the graph that AFSnW.DLP outperforms the other two schemes for almost all values of L. Moreover, we notice that the bad choice of the drop-least-priority policy rendered AFSnW.DO very close or even worse than SW at some points in the graph. That is why in the implementation of AFSnW, there should be clear distinction between the priority scheme that dictates what messages to be transmitted first upon a contact and the dropping policy that determines which messages to be dropped upon an overflow in the buffer capacity. The latter does not need to depend on the priority scheme and is recommended to be a drop-oldest policy, which does not distinguish between prioriy levels.

4) *Overhead Comparison*

Since FS has no limit on the number of replicas per message, except the limitation of the contact schedule, Figure 7 shows that it results in at least 5 to 6 times more overhead than the other schemes. On the other hand, SW and FSnW remain comparable, and the slight difference is mainly due to the prioritization in the buffer. In this way, smaller messages are allowed to be exchanged with a higher priority and consequently will be transmitted during the contact time. This reduces the number of unsuccessful deliveries and consequently the overhead.

V. Conclusion and Future Work

In this paper, we have targetted the optimization of spray-based opportunistic routing schmes, particulary improving their probability of delivery and latency while benefiting from their low overhead. We introduced Adaptive Fuzzy Spray and Wait, a novel routing protocol that works on the buffer prioritization level. It uses a fuzzy decision making technique to classify messages into levels inside the buffer, promoting high priority ones during contact times. In parallel, it uses a randomized buffer dropping policy in order to target the fairness issue and to allow a better perfomance in face of contention. Its adaptability to the network parameters greatly enhances its perfomance under high mobility scenarios. We comprehensively compared AFSnW to the other schemes through simulation. More comprehensive simulations and an analytical modelling of AFSnW appear in the full paper [24] and were omitted from this work for space constraints.

We are planning to provide a more elaborate optimization of AFSnW, including a thorough analytical modeling under more realistic mobility models, and new ways of increasing its efficiency. We aim that through this comprehensive system, with optimized routing and multiple opportunities, we will be able to reach the optimal combination between overhead, latency, and probability of delivery.

References

[1] A. Keränen, “The ONE Simulator for DTN Protocol Evaluation,” *Proceedings of the Second International ICST Conference on Simulation Tools and Techniques*, 2009.

[2] K.A. Harras, M.P. Wittie, K.C. Almeroth, and E.M. Belding, “ParaNets: a parallel network architecture for challenged networks,” *Proceedings of the IEEE Workshop on Mobile Computing Systems and Applications, IEEE Computer Society Press, Los Alamitos*, Citeseer, 2007, pp. 73-78.

[3] T. Small and Z.J. Haas, “The shared wireless infostation model: a new ad hoc networking paradigm (or where there is a whale, there is a way),” *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing*, ACM New York, NY, USA, 2003, p. 233–244.

[4] D. Goodman, J. Borras, N. Mandayam, and R. Yates, “Infostations: A new system model for data and messaging services,” *1997 IEEE 47th Vehicular TeFSchnology Conference*, 1997.

[5] R.C. Shah, S. Roy, S. Jain, and W. Brunette, “Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks,” *Proceedings of the First IEEE International Workshop on Sensor Network Protocols and Applications*, 2003.

[6] J. LeBrun, C.N. Chuah, D. Ghosal, and M. Zhang, “Knowledge-based opportunistic forwarding in vehicular wireless ad hoc networks,” *IEEE Vehicular Technology Conference*, Citeseer, 2005, p. 2289.

[7] L. Pelusi, A. Passarella, and M. Conti, “Opportunistic networking: data forwarding in disconnected mobile ad hoc networks,” *IEEE Communications Magazine*, vol. 44, Nov. 2006, pp. 134-141.

[8] A. Lindgren, A. Doria, and O. Schelén, “Probabilistic routing in intermittently connected networks,” *Lecture Notes in Computer Science*, 2004, p. 239–254.

[9] B. Burns, O. Brock, and B.N. Levine, “MV routing and capacity building in disruption tolerant networks,” *IEEE infocom*, Citeseer, 2005, p. 398.

[10] J. Burgess, B. Gallagher, D. Jensen, and B.N. Levine, “Maxprop: Routing for vehicle-based disruption-tolerant networks,” *Proc. IEEE Infocom*, Citeseer, 2006, pp. -292006pp1-11.

[11] P. Hui, J. Crowcroft, and E. Yoneki, “Bubble rap: Social-based forwarding in delay tolerant networks,” *Proceedings of the 9th ACM international symposium on Mobile ad hoc networking and computing*, ACM, 2008, p. 241–250.

[12] A. Mathurapoj, C. Pornavalai, and G. Chakraborty, “Fuzzy-spray: efficient routing in delay tolerant ad-hoc network based on fuzzy decision mechanism,” *Fuzzy Systems, 2009. FUZZ-IEEE 2009. IEEE International Conference on*, IEEE, 2009, p. 104–109.

[13] T. Spyropoulos, K. Psounis, and C.S. Raghavendra, “Spray and wait: an efficient routing scheme for intermittently connected mobile networks,” *Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking*, ACM, 2005, p. 259.

[14] T. Spyropoulos, K. Psounis, and C.S. Raghavendra, “Efficient Routing in Intermittently Connected Mobile Networks: The Multiple-Copy Case,” *IEEE/ACM Transactions on Networking*, vol. 16, 2008, pp. 77-90.

[15] A. Jindal and K. Psounis, “Contention-Aware Performance Analysis of Mobility-Assisted Routing,” *IEEE Transactions on Mobile Computing*, vol. 8, Feb. 2009, pp. 145-161.

[16] Y. Shi and R. c Eberhart, “Fuzzy adaptive particle swarm optimization,” *Proceedings of the 2001 Congress on Evolutionary Computation (IEEE Cat. No.01TH8546)*, IEEE, 2001, pp. 101-106.

[17] E. Cox, “Adaptive fuzzy systems,” *Spectrum, IEEE*, 2002.

[18] T. Spyropoulos, A. Jindal, and K. Psounis, “An analytical study of fundamental mobility properties for encounter-based protocols,” *International Journal of Autonomous and Adaptive Communications Systems*, vol. 1, 2008, p. 4.

[19] C. Bettstetter, H. Hartenstein, and X. Pérez-Costa, “Stochastic properties of the random waypoint mobility model,” *Wireless Networks*, vol. 10, 2004, p. 555–567.

[20] R. Park, “Impact of vehicle movement models on VDTN routing strategies for rural connectivity Vasco N.G.J. Soares,” *Design*, vol. X, 1801.

[21] P. Ginzboorg, V. Niemi, and J. Ott, “Message Fragmentation in Disruptive Networks,” *74.52.83.98*, 2009.

[22] H.T. Nadu and T. Nadu, “Effective Buffer Management and Scheduling of bundles in Delay Tolerant Networks with finite buffers,” pp. 1-4.

[23] I. Kay, *A Survey of Fuzzy Logic and Applications*, 1994.

[24] H. Harkous, J. Makhlouta, F. Hutayt, H. Artail. Adaptive Fuzzy Spray and Wait: Efficient Routing for Opportunistic Networks. Technical Report EPFL-REPORT-168629, September 2011, Also available at http://infoscience.epfl.ch/record/168629.